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Foraminifera from microtidal rivers with large seasonal salinity variation, southwest Western Australia *

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Large seasonal variations in salinity due to microtidal conditions and highly seasonal rainfall occur in the tidal reaches of the Serpentine River (51 maximum salinity variation), Murray River (38) and Collie River (32) which flow into large estuarine lagoons in southwest Western Australia. Preliminary observations are made on the distributions of foraminifera in these rivers that may reflect salinity changes. Thirty-five foraminiferal species are recorded from the rivers, including 10 species from the Serpentine River, 14 species from the Murray River and 33 species from the Collie River. Live foraminifera, determined by Rose-Bengal staining are very rare. The total (dead + live) foraminiferal assemblage is dominated by few species groups including hyaline *Ammonia* gr. *tepida*, *Elphidium* gr. *gunteri*, *E.* gr. *excavatum* and *E.* gr. *advenum*, porcelaneous *Quinqueloculina* gr. *seminula*, and organic-cemented agglutinated *Ammobaculites exiguus*. Among the live hyaline foraminifera, *Ammonia* gr *tepida* shows the greatest tolerance to salinity variation, occupying the entire 51 range recorded in the rivers. Live *Elphidium* gr. *gunteri*, *E.* gr *excavatum* and *E.* gr. *advenum* are found only at salinities less than about 44, extending to salinities of below 1. The dominant porcelaneous group, thin-walled small *Quinqueloculina* gr. *seminula*, lives in the rivers through a salinity range of 24–45 and shows progressive decrease in test size upstream from the river mouths. The agglutinated *Ammobaculites exiguus* is only common in the Serpentine River where it probably tolerates a very large salinity range. In the Murray and Collie Rivers organic-cemented agglutinated foraminifera are rare; and carbonate-cemented agglutinated forms are absent from all the rivers. Apart from the dominant species, most of the other hyaline and porcelaneous species seem to be confined, in both the dead and live assemblages, to the lower reaches of the rivers, where most live representatives are present under salt-wedge conditions approaching normal-marine salinities.

KEYWORDS: Collie River, foraminifera, Murray River, salinity distribution, Serpentine River, Western Australia.

INTRODUCTION

Lower reaches of rivers located in areas with highly seasonal rainfall and microtidal (<2 m) conditions are influenced by extreme seasonal variations in water quality due to variable freshwater outflow and the tidal forcing of inflowing marine water. This variability affects salinity, temperature, dissolved oxygen, light penetration, turbidity, suspended matter, nutrients and pH within the tidal reaches of the rivers and changes throughout the year. Because of warm dry summers and cool wet winters, coastal rivers of southwest Australia, particularly those that flow into large estuarine lagoons, display these characteristics (Brearley 2005; de Lestang *et al.* 2003; Gerritse *et al.* 1998; Kurup *et al.* 1998; McComb *et al.* 1998; Stephens & Imberger 1996).

Foraminiferal distributions in marginal-marine environments vary according to salinity, although other factors may also influence the distribution patterns (Murray 1991, 2006). Worldwide, there have been few studies of foraminiferal distributions in tidal rivers with seasonal salinity variations greater than 30 (Debenay *et al.* 1989, 2006; Murray 1991, 2006; Reddy & Rao 1984). In southwest Australia, the microtidal lower reaches of the Serpentine River, which flows into a large estuarine lagoon (Peel Inlet: Figure 1), recorded winter wet-season to summer dry-season variation in salinity of up to 51 during 2005–2006. Also within the region, during the same period, the microtidal reaches of the Murray River (flowing into Peel Inlet: Figure 1) and the Collie River (flowing into Leschenault Estuary: Figure 1) experienced large but less extreme salinity variations (up to 38 and 32 respectively). These rivers are excellent sites to study the influence of seasonal salinity changes on foraminiferal distributions in microtidal rivers whose entrances are located at varying distances across shallow estuarine lagoons from the open-marine shelf.

The aim of this paper is to make preliminary observations on the foraminiferal distributions in the microtidal Serpentine, Murray and Collie Rivers that flow into large estuarine basins in southwest Western Australia. Very large seasonal changes in salinity characterise the rivers and doubtless have a major influence on the fauna. This study adds significant data to knowledge of estuarine foraminifera in this part of Australia and will eventually contribute, when faunas from other microtidal rivers in the region become known, to more detailed biogeographic comparisons with estuarine foraminifera elsewhere.

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* Tables 1–5, indicated with an asterisk (*) in the text, are Supplementary Papers available from the Society's Library (held in the Western Australian Museum, 49 Kew Street, Welshpool, WA 6106) or from the Society's website.

REGIONAL SETTING

Geomorphology, freshwater inflow and salinity

The study area is located on the Swan Coastal Plain in southwest Western Australia (Figure 1). The Peel–Harvey Estuary is located on the western edge of the Swan Coastal Plain, about 80 km south of Perth (Brearley 2005), and consists of two interconnected coastal plain lagoons, the Peel Inlet and the Harvey Estuary (Gabrielson & Lukatelich 1985) (Figure 1). The total area of the Peel–Harvey Estuary is just over 135 km², and the Peel Inlet and Harvey Estuary are the largest inland water bodies in southwest Western Australia (Brearley 2005). The three rivers that flow into the Peel–Harvey Estuary are the Murray and Serpentine Rivers, located to the northwest of the Peel Inlet, and the Harvey River, located to the south of Harvey Estuary. The total catchment area of Peel–Harvey Estuary is 11 300 km², and total freshwater inflow to the estuary averages 430 x 10^6 m³/year (Brearley 2005). The major source of freshwater is from the Murray River, with a catchment area of 6890 km² accounting for 60% of discharge. Around 12% of discharge into the Peel–Harvey Estuary occurs from the Serpentine River and 20% from the Harvey River (Brearley 2005).

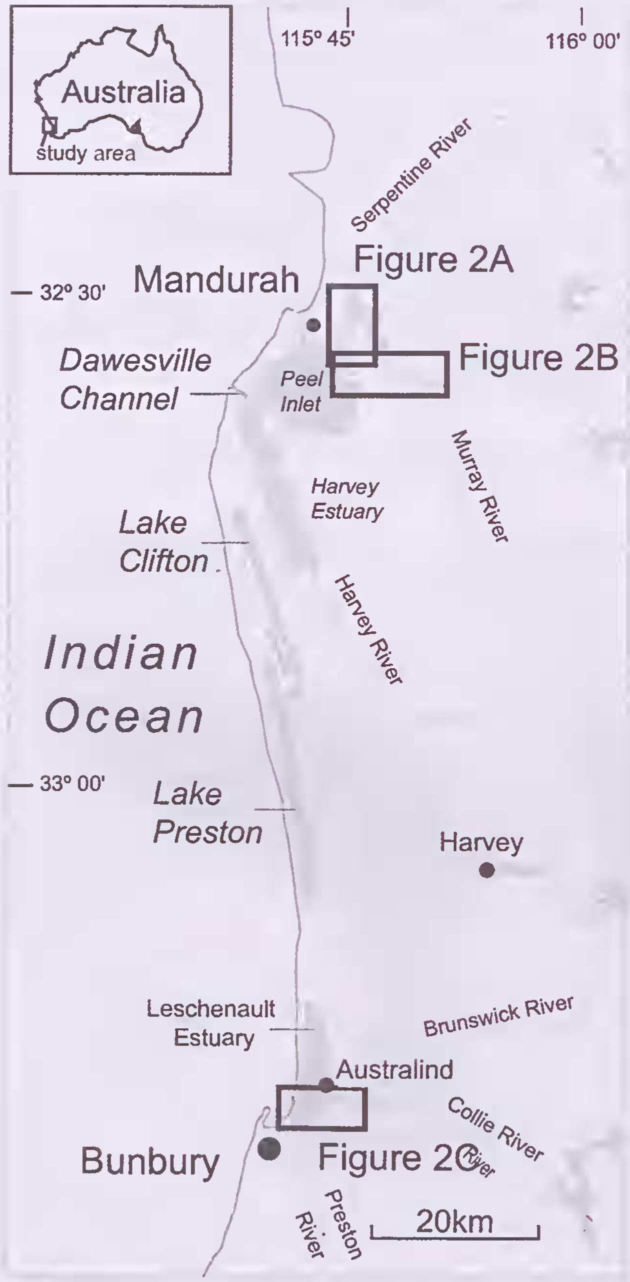

Figure 1 Map of the Swan Coastal Plain in southwest Australia showing the location of studied rivers.

The Leschenault Inlet (Figure 1) is an elongate shore-parallel lagoon located on the southern edge of the Swan Coastal Plain (Semeniuk *et al.* 2000). The estuary is 14 km long and 1.5–2.5 km wide, with a total area of about 27 km². The Collie River and the Preston River are the two river systems fluvially influencing the Leschenault Estuary (Semeniuk *et al.* 2000). Both rivers are located to the south of the estuary. The catchment area of the Leschenault Estuary is 4600 km². The Collie and Preston Rivers drain a total of 3600 km², although Wellington Dam traps the majority of the water. River discharge into the Leschenault Estuary occurs from a 770 km² area, of which 603 km² is drained by the Preston River (Brearley 2005). River discharge from the Collie River occurs from an area of only 167 km².

Artificial channels connecting both the Peel–Harvey and Leschenault Estuaries to the Indian Ocean have been constructed. The Dawesville Cut, a 2.5 km long channel located to the north of the Harvey Estuary (Figure 1), was constructed in 1994 to increase flushing between the Peel–Harvey Estuary and the ocean (Brearley 2005). A channel simply known as The Cut (Figure 2c) was opened in 1951 in the Leschenault Estuary, to increase drainage and reduce flooding (Semenuik *et al.* 2000). The opening of the channels has caused a marked increase in the influence of marine water in the lower reaches of the Serpentine, Murray and Collie Rivers, the three rivers chosen for this study.

De Lestang *et al.* (2003) plotted mean monthly salinities in the Peel Inlet, Harvey Estuary and Serpentine River for pre-Dawesville Cut (1980–1981) and post-Dawesville Cut (1995–1998) periods, and noted that during October to December mean monthly salinities were about 10–21 higher in the 1995–1998 interval compared to the 1980–1981 period. Their generalised data showed that after the Dawesville Cut was constructed mean monthly salinities in the main estuarine lagoon (Peel Inlet) varied from just above 40 in December–January to below 20 in August. The mouths of the Serpentine and Murray Rivers lie over 5 km across Peel Inlet from the natural open-marine inlet channel at Mandurah (Figure 1) and over 12 km across the estuarine lagoon from the artificial Dawesville Cut (Figure 2), the other open-marine inlet channel to the estuarine system. In contrast the mouth of the Collie River lies within 2 km of the open-marine channel to the Leschenault Inlet and is influenced by estuarine lagoon waters with an annual salinity variation of from about 29 at the end of winter to about 37 at the end of summer (Semeniuk *et al.* 2000).

Climate

The southwest of Western Australia is characterised by a temperate Mediterranean climate, with warm dry

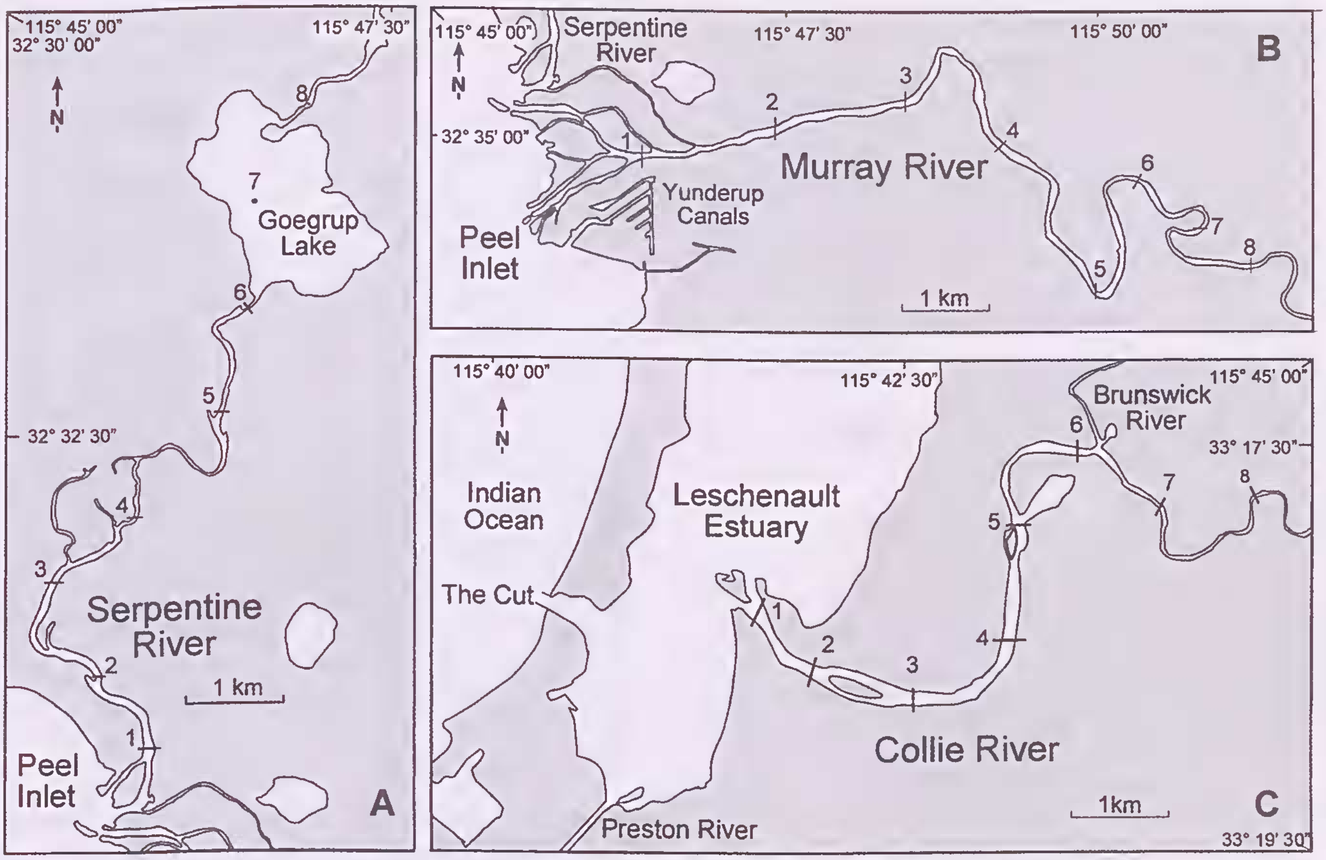

Figure 2 Location of studied transects in the Serpentine River (a), Murray River (b) and Collie River (c).

summers and cool wet winters. Average annual rainfall for Mandurah and Bunbury is 875 mm and 861 mm respectively. Rainfall is highly seasonal (Figure 3), with 90% of rainfall falling between May and October (Brearley 2005), though up to 95% of freshwater runoff has been recorded between June and September (C Wilson, J Hale & E I Paling unpubl. 1997 data). Mean annual evaporation is around 1750 mm, and similar to rainfall, is highly seasonal (C J Hearn, R J Lukatelich & J R Hunter unpubl. 1986 data).

The daily open ocean tidal range is around 0.6–0.7 m, and although there are no tide predictions for the Leschenault Estuary, in Peel Inlet the tidal range is around 0.4–0.5 m (www.bom.gov.au). The phase of the diurnal tide varies by 24 hours throughout the year, so that the ebb tide occurs during the night in summer, and during the day in winter (C J Hearn, R J Lukatelich & J R Hunter unpubl. 1986 data).

The mean maximum and minimum atmospheric temperatures experienced by Mandurah at the mouth of the Peel–Harvey Estuary are 29.5°C and 15.3°C in summer, and in winter, 17.3°C and 8.6°C. Summer maximum and minimum temperatures for Bunbury at the mouth of the Leschenault Estuary are 27.8°C and 13.9°C, and in winter 16.8°C and 8.4°C respectively (www.weatherbase.com).

Previous research

Published water-quality data on estuarine environments in southwest Western Australia is focused on the larger coastal estuaries, or on rivers that drain directly into the ocean (Brearley 2005; Semenuik *et al.* 2000). Comparatively little has been published on the tidal rivers that drain into the estuarine lagoons. The Serpentine, Murray and Collie Rivers and their associated estuaries were not included in the study of riverine sediment loads and the relationship between sediment and water quality in the wave-dominated estuaries of southwest Australia reported on by Radke *et al.* (2004).

Little has been published on the foraminiferal distributions in microtidal rivers in southwest Australia. The main studies have been performed on the large coastal estuaries (McKenzie 1962; Quilty 1977; Revets 2000; Quilty & Hosie 2006). Quilty's (1977) study on the Hardy Inlet, to the south of the present study area, and McKenzie's (1962) study of Oyster Harbour near Albany on the southern coast of Western Australia included a few localities in the lower reaches of tidal rivers associated with the estuaries. None of these investigations included an analysis of the influence of seasonal variation on the foraminiferal distributions in the tidal rivers or in the estuaries.

METHODS

Study sites

The Serpentine, Murray and Collie Rivers were sampled on three occasions, from 18–20 August 2005 (peak freshwater outflow, minimum tidal influence), 2–4 November 2005 (decreasing freshwater outflow) and the

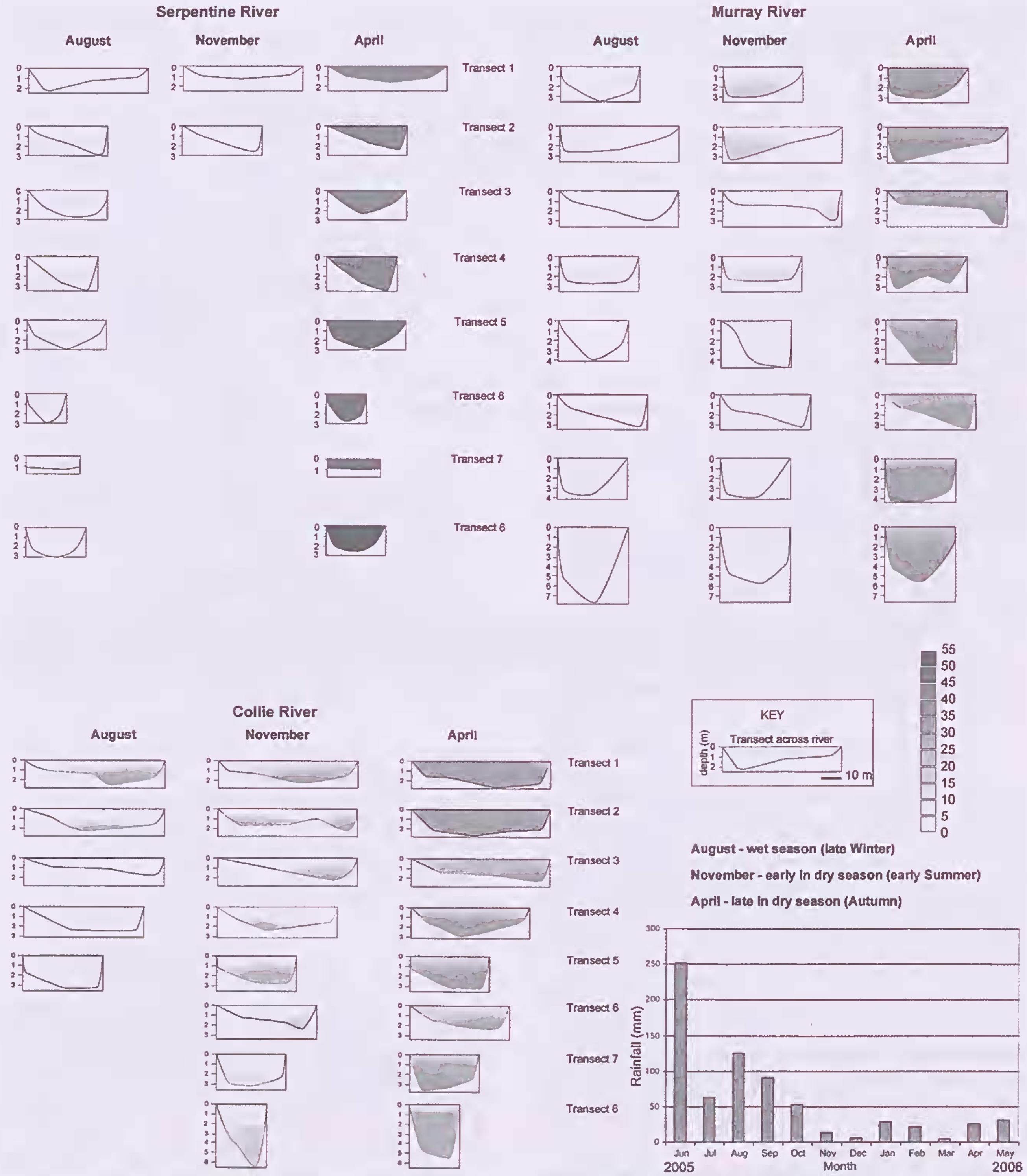

Figure 3 Salinity profiles for studied transects in each river during the August and November 2005 and April 2006 sampling periods. Also shown is a plot of average monthly rainfall from June 2005 to May 2006 (data from www.bom.gov.au).

5–7 April 2006 (negligible rainfall, maximum tidal influence) to gain an understanding of the annual variability in water quality. The rivers were not sampled in late January or February, as the summer of 2005–2006 was wetter, and the autumn drier, than long-term averages. Along about the lower 10 km of each river, eight transects (perpendicular to the river bank) were selected (Figure 2), and on each transect data on bathymetry and water quality was obtained and a sediment sample retrieved, usually from three sites. Two of the sample sites were positioned 4–5 m from opposite sides of the river and one site was positioned at the centre of the river. Where transect distance was 60 m or greater, four sites were sampled with the central localities positioned about 20–25 m from each bank. Samples were numbered according to transect and a numerical series starting from the left side of the river when facing upstream.

Salinity and sediment sampling

Because of the importance of salinity in controlling foraminiferal distributions (Murray 1991, 2006) and because salinity is one of the most variable features of the studied rivers, the relationship between salinity and the distribution of foraminiferal species is the focus of this study. Salinity was measured using a Hydrolab multiprobe at each sample site (Table 1*). Foraminifera live on or within the sediment forming the riverbed. Sediment was sampled using a sediment corer of 4 cm diameter, attached to a metal pole, operated from a boat. The top 2–3 cm of the recovered core was placed into a sample vial and stored in an icebox. Samples were stained with Rose Bengal one day after collection, and then wet sieved through 1 mm, 150 μm and 63 μm mesh. The sediment fractions were examined separately for foraminiferal analyses. In additional to salinity, water temperature and pH were measured as well as dissolved oxygen for some samples (Table 1*). Grainsize analysis was also undertaken using a Sedigraph X-ray attenuation instrument for the fraction less than 3.25 Φ (106 μm), and using a settling tube for the >106 μm fraction (Table 2*).

Foraminiferal analysis

All sediment samples were first examined to determine which species were present. The 1 mm–150 μm fraction for the most diverse sample in each transect collected during August and April was then systematically picked. For each of these samples, an attempt was made to pick 200 specimens in a total pick (dead and live individuals) and 100 in a pick of live individuals (identified by Rose Bengal staining), but for many of the samples this was not possible particularly for the live assemblage. As well as the total systematic pick, where possible an additional search for very rare species was made. Live foraminifera, identified by Rose Bengal staining, were extremely rare and in all samples the total pick approximates the dead assemblage. Due to the difficulty in identifying living agglutinated species with Rose Bengal the analysis of the live microfauna is limited to hyaline and porcelaneous species.

For the August samples, species were classified as being present or absent, and clustered using the Jaccard Index and the UPGMA method in MVSP 3.1.The statistical foraminiferal data was clustered using the Bray–Curtis method, with data square-root transformed, as clustering using the Bray–Curtis method with unweighted data has been recognised as producing clusters influenced by high values (Stephenson 1973; Michie 1982). Foraminifera and washed-sediment residues recovered in this study are in the collections of the Edward de Courcy Clarke Earth Science Museum at the University of Western Australia.

RESULTS

Salinity

Due to variation in rainfall between wet winters and dry summers significant seasonal changes in salinity take place in each river (Table 1*). Salinity profiles (Figure 3) observed at each transect early in the dry season (November 2005), late in the dry season (autumn 2006), and during the wet season (August 2006) illustrate major differences between the rivers. Salinity stratification was most apparent in the Collie River at all measuring times, and in the records taken from the Murray River during November and April. The highest salinities were found throughout the Serpentine River during the April sampling.

In the bottom waters of all the rivers (Figure 4), except near the mouth of the Collie River, salinities lower than 2 are present during the wet season and salinities higher than 30 prevail at the end of the dry season. The maximum variation between wet- and dry-season bottom-water salinities of slightly over 50 was found in

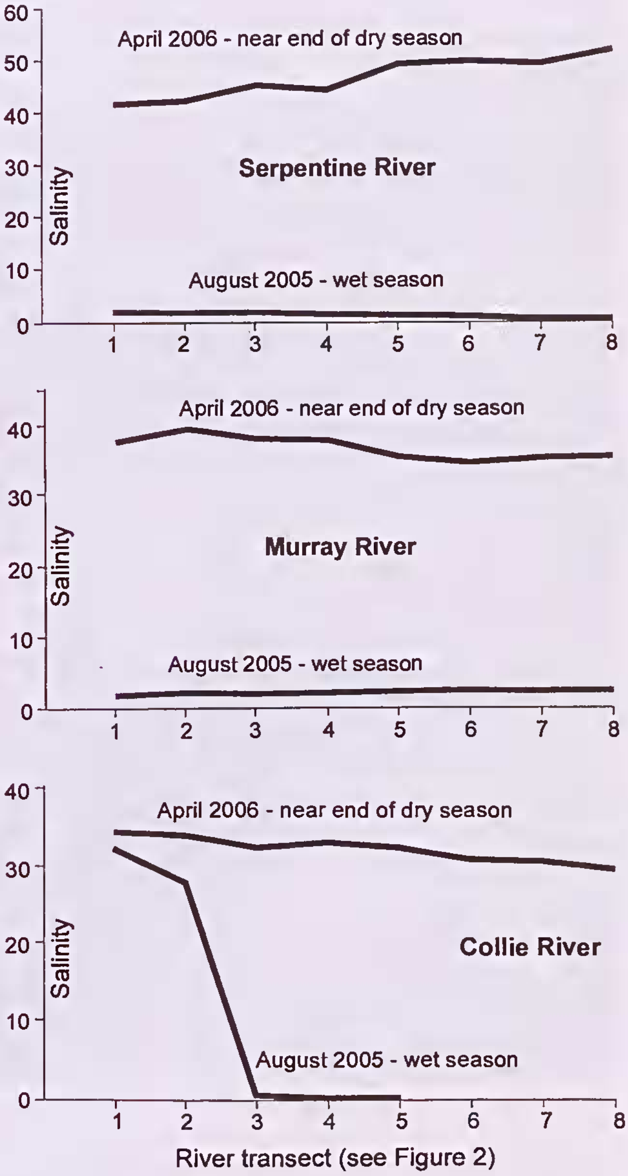

Figure 4 Comparison of bottom-water salinity at each river transect between the August 2005 wet season and the April 2006 end of dry season. The salinity measurements are those from the deepest part of the river sampled on each transect.

transect 8 of the Serpentine River. During the dry season, bottom-water salinities in the Murray and Collie Rivers decrease slightly upstream, whereas those in the Serpentine River show a slight increase upstream.

The reasons for the salinity differences between rivers are probably: (i) the broader estuarine lagoon of lower winter salinity into which the Serpentine and Murray Rivers flow compared to the narrow southern part of the Leschenault Estuary (of almost normal-marine salinity in winter) into which the Collie River flows; (ii) the smaller freshwater catchment area and therefore lower freshwater outflow in the Collie River compared to the other rivers; and (iii) the deeper less-restricted river channel in the Murray River compared to the Serpentine River; and the broad very shallow Goegrup Lake on the Serpentine River (Figure 2a) that because of evaporation may be responsible for elevated salinities here during the dry season.

Foraminiferal distributions

Thirty-five foraminiferal species have been found in the studied rivers (Figures 5, 6; Appendix 1). These include types well known from estuaries and tidal rivers elsewhere in Australia and on other continents. As demonstrated by Hayward *et al.* (2004) in their study of *Ammonia*, the taxonomy of many of the species, even those most widely recorded, is poorly understood. For this reason we have used broad species groups for some taxa (e.g. *Ammonia* gr. *tepida*) rather than more precise determinations.

LIVING (STAINED) ASSEMBLAGES

Only hyaline and porcelaneous species are considered here because of the difficulty in recognising stained individuals among the agglutinated foraminifera. The total (living plus dead) distribution of foraminiferal tests (see below) suggests that organic-cemented agglutinated foraminifera live through a broad salinity range in the rivers. Tables 3*–5* record the August (wet season) and April (dry season) fauna living in each river and Figure 7 summarises these distributions against salinity. The results presented here are preliminary and based on low stained-specimen counts and on the assumption that tests

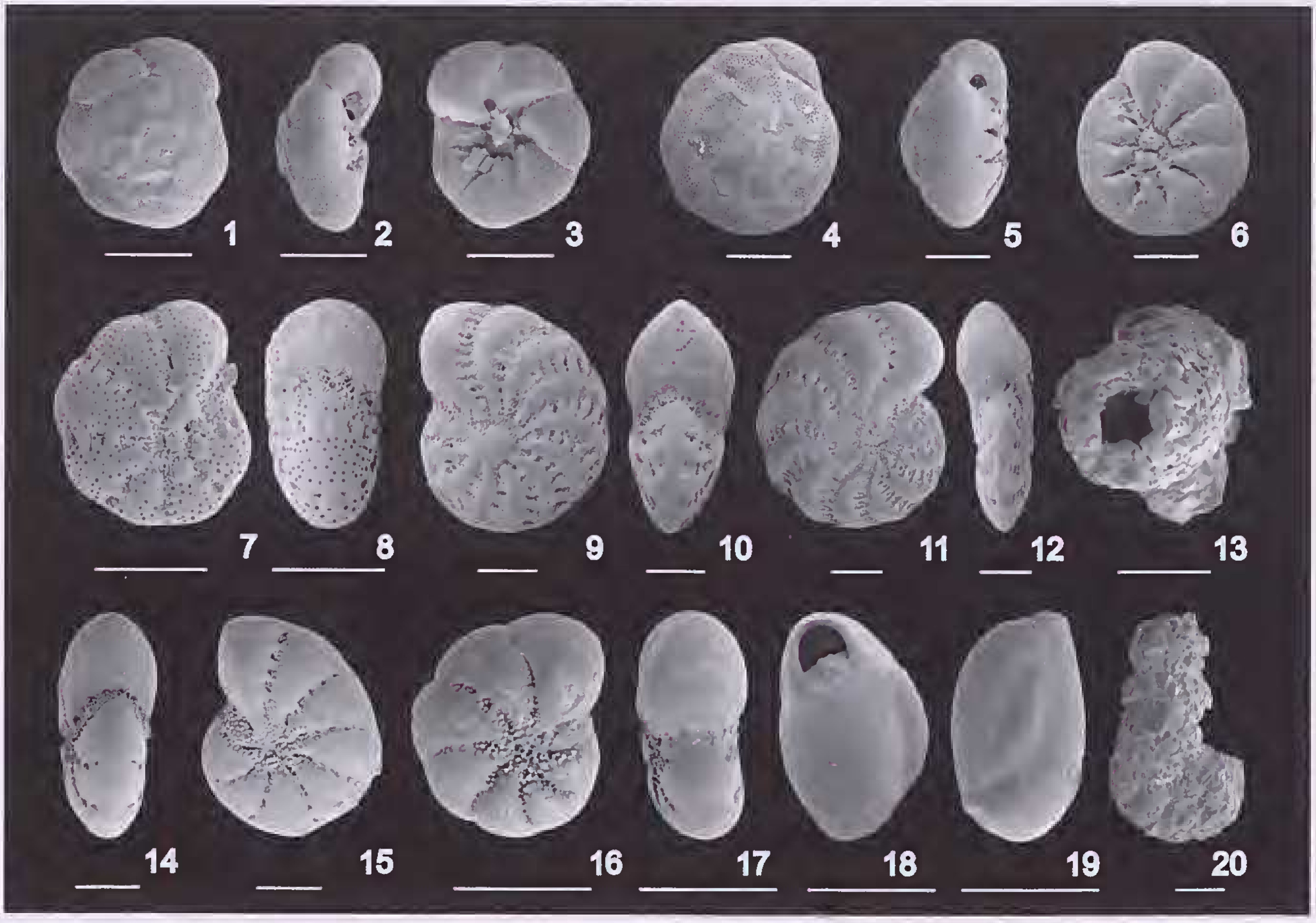

Figure 5 Dominant foraminiferal species; secondary electron images. Scale bars are 0.1 mm. (1–3) *Ammonia* gr. *tepida* (Cushman), from Murray River: (1) spiral view, (2) peripheral view, (3) umbilical view. (4–6) *Ammonia* gr. *tepida* (Cushman), from Murray River: (4) spiral view, (5) peripheral view, (6) umbilical view. (7, 8) *Elphidium* gr. *gunteri* Cole, from Murray River: (7) lateral view, (8) peripheral view. (9, 10) *Elphidium advenum* (Cushman), from Collie River: (9) lateral view, (10) peripheral (apertural) view. (11, 12) *Elphidium* cf. *advenum* (Cushman), from Collie River: (11) lateral view, (12) peripheral view. (13, 20) *Ammobaculites exiguus* Cushman & Bronnimann, from Serpentine River: (13) apertural view, (20) lateral view. (14, 15) *Elphidium excavatum* (Terquem), from Collie River: (14) peripheral view, (15) lateral view. (16, 17) *Elphidium* cf. *excavatum* (Terquem), from Murray River: (16) peripheral view, (17) lateral view. (18, 19) *Quinqueloculina* gr. *seminula* (Linnaeus), from Collie River: (18) apertural view, (19) lateral view.

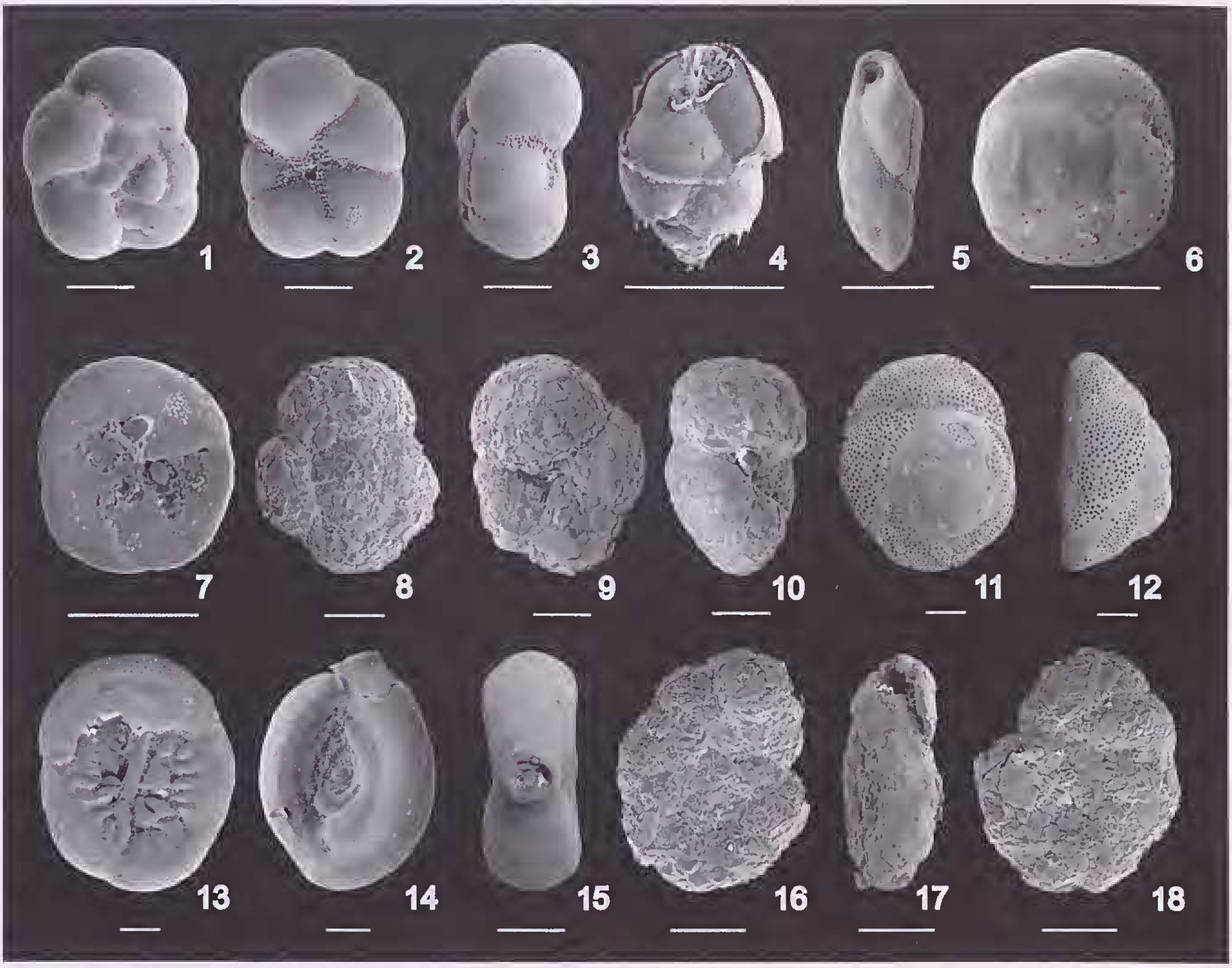

Figure 6 Rare foraminiferal species not previously illustrated from estuaries in southwest Australia; secondary electron images. All specimens from the Collie River. Scale bars are 0.1 mm. (1–3) *Aubignyna* sp.: (1) spiral view, (2) umbilical view, (3) peripheral view. (4) *Bulimina marginata* d'Orbigny: lateral view. (5) *Buliminella elegantissima* d'Orbigny: lateral view. (6, 7) *Neoconorbina* sp.: (6) spiral view, (7) umbilical view. (8–10) *Paratrochammina* sp.: (8) spiral view, (9) umbilical view, (10) peripheral view. (11–13) *Rosalina* sp.: (11) spiral view, (12) peripheral view, (13) umbilical view. (14, 15) *Spiroloculina* sp.: (14) lateral view, (15) peripheral view. (16–18) *Trochammina*? sp.: (16) umbilical view, (17) peripheral view, (18) spiral view.

showing internal red staining represent live individuals. In future studies, examination of larger sediment samples may yield greater specimen counts that may be statistically treated; and a combination of CellTracker Green and Rose Bengal staining viewed under epifluorescence microscopy (Bernhard *et al.* 2006) may provide better detection of living individuals.

In the Serpentine River, the assemblage during August (wet season) was dominated by *Ammonia* gr. *tepida*. *Elphidium* gr. *gunteri* and *Elphidium* gr. *excavatum* were the only other species groups living in the river. The numbers of living foraminifera were sparse, and populations of individual species were highest toward the river mouth. In contrast to the wet season pattern, six of seven hyaline and porcelaneous species in the overall (dead + living) assemblage were living in April at the end of the dry season. The diversity of the living assemblage steadily decreased from transects 1 to 5 and *Ammonia* gr. *tepida* was the only species that was living upstream from transect 5.

The distribution of foraminifera living in the Murray River in August was similar to that in the Serpentine River. *Ammonia* gr. *tepida* was the most common living species group, and *Elphidium* gr. *gunteri* was living mainly toward the river mouth. Living individuals decreased in abundance upstream, although the trend was not as noticeable as in the Serpentine River. Three species groups, *Ammonia* gr. *tepida*, *Elphidium* gr. *gunteri* and *Quinqueloculina* gr. *seminula* were living at more than one location in the Murray River during April. Two of these groups, *A.* gr. *tepida* and *E.* gr. *gunteri* were living throughout the river during this month, whereas *Q.* gr. *seminula* was living mainly in transects 1 and 2. *Cornuspira planorbis* was living in one sample, and *Elphidium excavatum* subsp. 2 was living in one sample and inconclusively stained in two others.

The highest number of living species during the wet season (August) was in the Collie River. Although a total of nine different species (and possibly two others) were stained, only three species groups, *Quinqueloculina* gr.

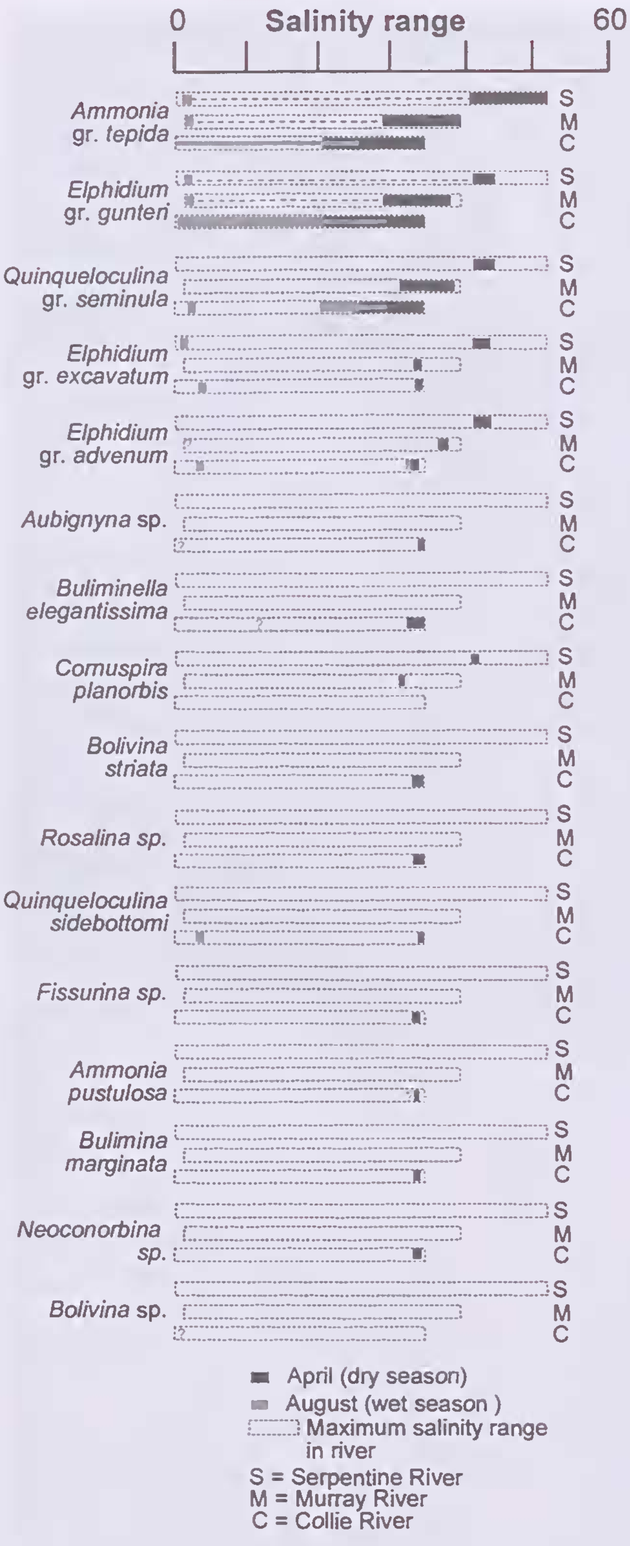

Figure 7 Summary of the distributions of living (Rose-Bengal stained) foraminifera plotted against salinity. Distributions in each river are recorded in Tables 3*–5*.

seminula, *Ammonia* gr. *tepida* and *Elphidium* gr. *gunteri*, were living at more than one location. There was a marked decrease in living species upstream. Of the 24 hyaline and porcelaneous species found in the Collie River as dead or alive specimens, 16 were living in April (end of dry season). The majority of tests were living within the first two transects, or in the deeper sites of transects 3 and 4. As in the Murray and Serpentine Rivers, living specimens of *Ammonia* gr. *tepida* were present in each transect examined in the Collie River.

The decrease in diversity of foraminifera upstream from the mouth of each river is attributed to a decrease in salinity, as is the lower diversity found in the August wet season compared to the April dry season (Figure 7). The much greater diversity in the lower three transects (1–3) of the Collie River compared to the Serpentine and Murray River transects, is coincident with a greater marine influence in the Collie River throughout the year and the more stable bottom-water salinity conditions in transects 1–3 of this river. Of the hyaline species found in the rivers, *Ammonia* gr *tepida* is most tolerant to salinity variation, occupying the full salinity range available to it in the studied sections of each river. *Elphidium* gr. *gunteri*, *E.* gr. *excavatum* and *E.* gr. *advenum*, while not as abundant as *Ammonia* gr. *tepida* and less tolerant in the upper salinity range (>44), also have broad salinity ranges. Among the porcelaneous species, small thin-walled *Quinqueloculina* gr. *seminula* has the most extensive distribution in the rivers (mainly 24–45). The records of rare *Q.* gr. *seminula* and *Q. sidebottomii* at low salinities in transects 1 and 2 of the Collie River may be of living tests slightly displaced from more saline waters of the salt wedge in this section of the river.

TOTAL (DEAD PLUS LIVING) ASSEMBLAGES

A total of 10 foraminiferal species including three agglutinated, two porcelaneous and five hyaline species, were identified from the Serpentine River among the total assemblage (Figure 8) based on samples collected during August sampling. Living individuals form a very small component of the total assemblage. *Ammonia* gr. *tepida* dominates the total assemblage and *Ammobaculites exiguus* is the subdominant species. *Quinqueloculina* gr. *seminula* occurs with a frequency of about 10% in the total foraminiferal assemblage in sample S2.1, but is rare elsewhere in transects 1–6. All other species are present at frequencies less than 10% of the total assemblage in any one sample.

Based on presence and absence distribution of species, the samples collected from the Serpentine River cluster in two main groups, one present in transects 1–5 and the other recorded from transects 5–8 (Figure 8). Species diversity decreases upstream from nine species present in the transect 1–5 cluster, and four species present in the transect 5–8 cluster. *Ammobaculites exiguus*, *Ammonia* gr. *tepida*, *Elphidium* gr. *gunteri*, *Elphidium* gr. *excavatum* and *Quinqueloculina* gr. *seminula* each occur in at least 12 of the 13 samples making the transect 1–5 cluster. Porcelaneous species are present only in this cluster, with *Cornuspira planorbis* and *Quinqueloculina* gr. *seminula* most abundant closest to the river mouth. *Quinqueloculina* gr. *seminula* is very rare above transect 2 where it is represented by very small fragile tests. *Ammobaculites exiguus* and *Ammonia* gr. *tepida* are present in each sample of the transect 5–8 cluster in the upstream reach of the tidal river, and these are associated with sporadic *Elphidium* gr. *gunteri* and *Trochammina inflata*.

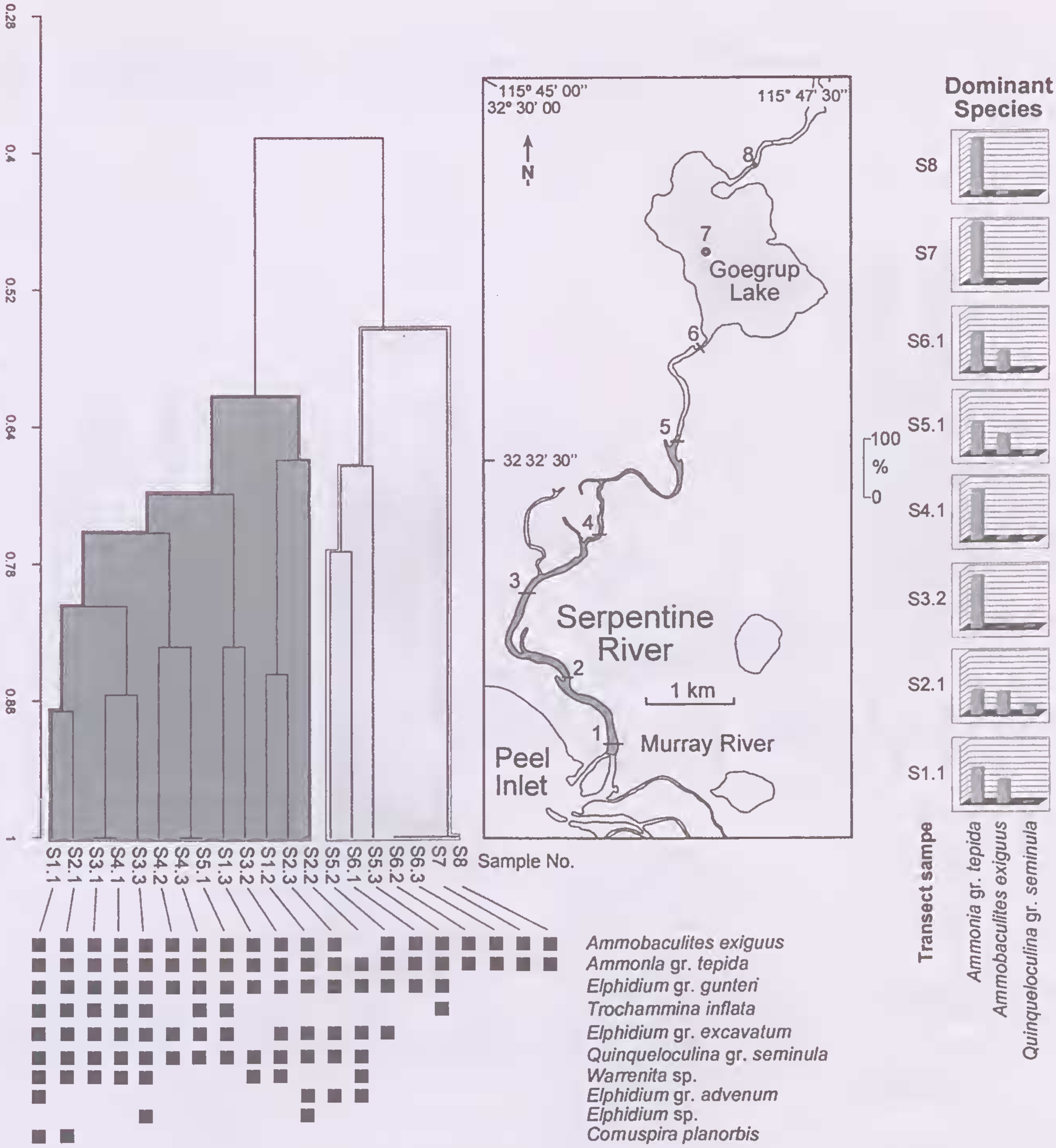

Figure 8 Distribution of foraminifera (total assemblage) from the Serpentine River during August 2005. Dominant species are those that have a frequency of ≥10% in one or more samples. The cluster analysis is based on the Jaccard Index and the UPGMA method in MVSP version 3.1.

In the Murray River the first transect undertaken during August sampling was located where the inlet channel had been dredged. There were almost no foraminifera in the sample from the dredged area, which was composed of compacted clay, and large proportions of reworked foraminifera were present in other samples in the transect. As these samples are not representative of modern conditions, sampling was moved about 300 m downstream in April (as shown in Figure 9). Samples were clustered using the samples collected in April.

A total of 14 species, five agglutinated, seven hyaline and two porcelaneous, were identified from the Murray River in the total foraminiferal assemblage (Figure 9). As in the Serpentine River, *Ammonia* gr. *tepida* is the dominant species, but *Elphidium* gr. *gunteri* is the only other species present at frequencies above 10% in at least one sample. In contrast to the Serpentine River, *Ammobaculites exiguus* was the least common agglutinated foraminifera in the Murray River. The most common agglutinated species is *Warrenita* sp.

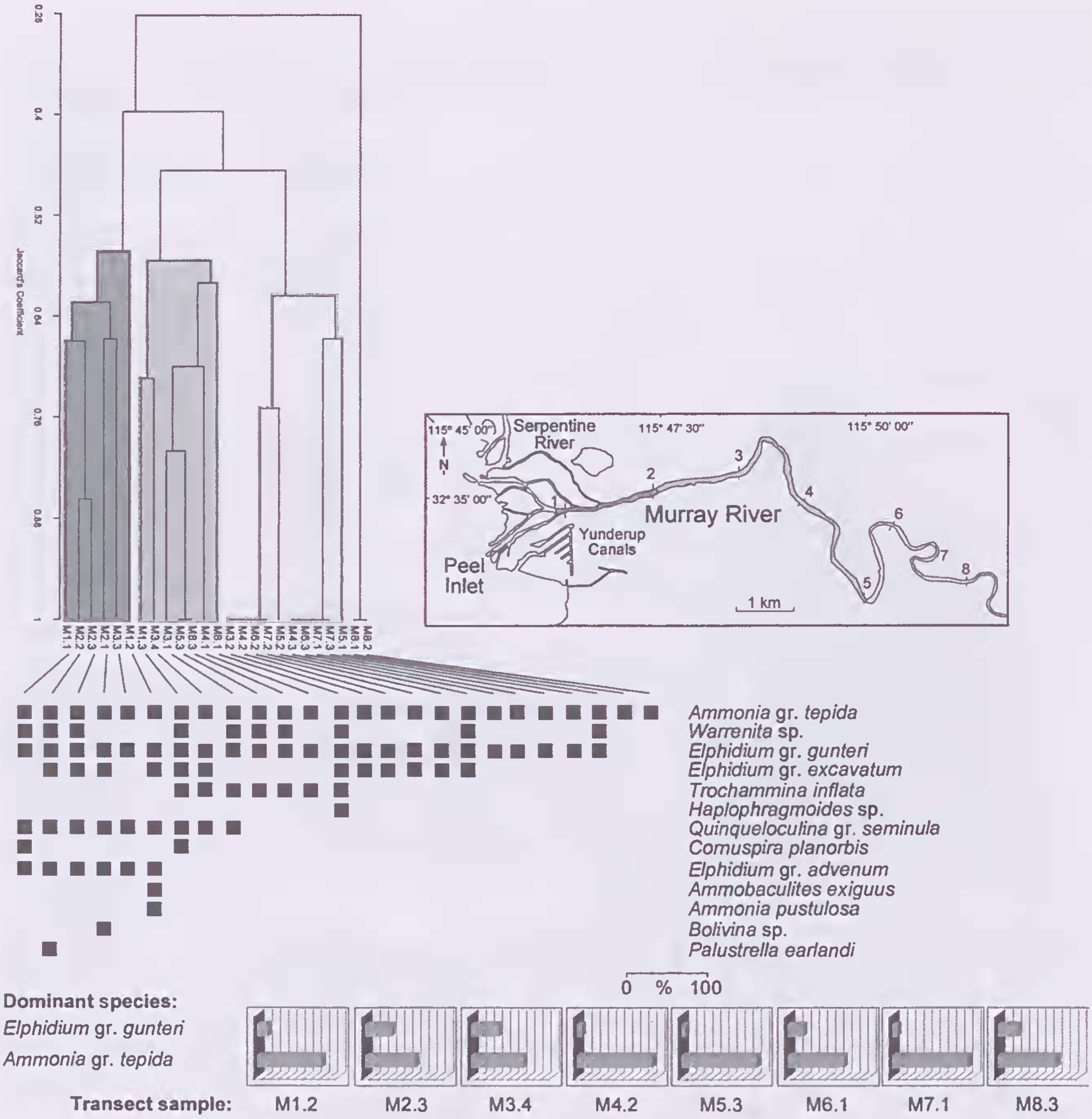

Figure 9 Distribution of foraminifera (total assemblage) from the Murray River during April 2006. Dominant species are those that have a frequency of ≥10% in one or more samples. The cluster analysis is based on the Jaccard Index and the UPGMA method in MVSP version 3.1.

Porcelaneous species (*Quinqueloculina* gr. *seminula* and *Cornuspira planorbis*) are present in transects close to the river mouth.

Based on presence–absence species distributions, three sample clusters were defined (Figure 9). These loosely distinguish upper, middle and lower reaches of the tidal river based on a decrease in species diversity upstream rather than on discrete suites of species. The lower cluster is made up of samples in transects 1–3. Most samples forming the middle cluster are from transects 3–6, with one sample from transect 1 and one from transect 8. Species diversity in some samples in the middle estuary section were lower than expected, and are clustered in the upstream cluster which includes samples from transects 3–8. This cluster pattern seems to be due to sediment grainsize because where samples were taken from well-sorted coarse sediment (e.g. samples M3.2, M4.2, M4.3, M5.2: Table 2*), species diversity and abundance are much lower than expected, and often *Ammonia* gr. *tepida* is the only species group present. Another anomaly in the cluster pattern is the presence of sample 8.3 in the middle cluster. In transect 8, sites M8.1

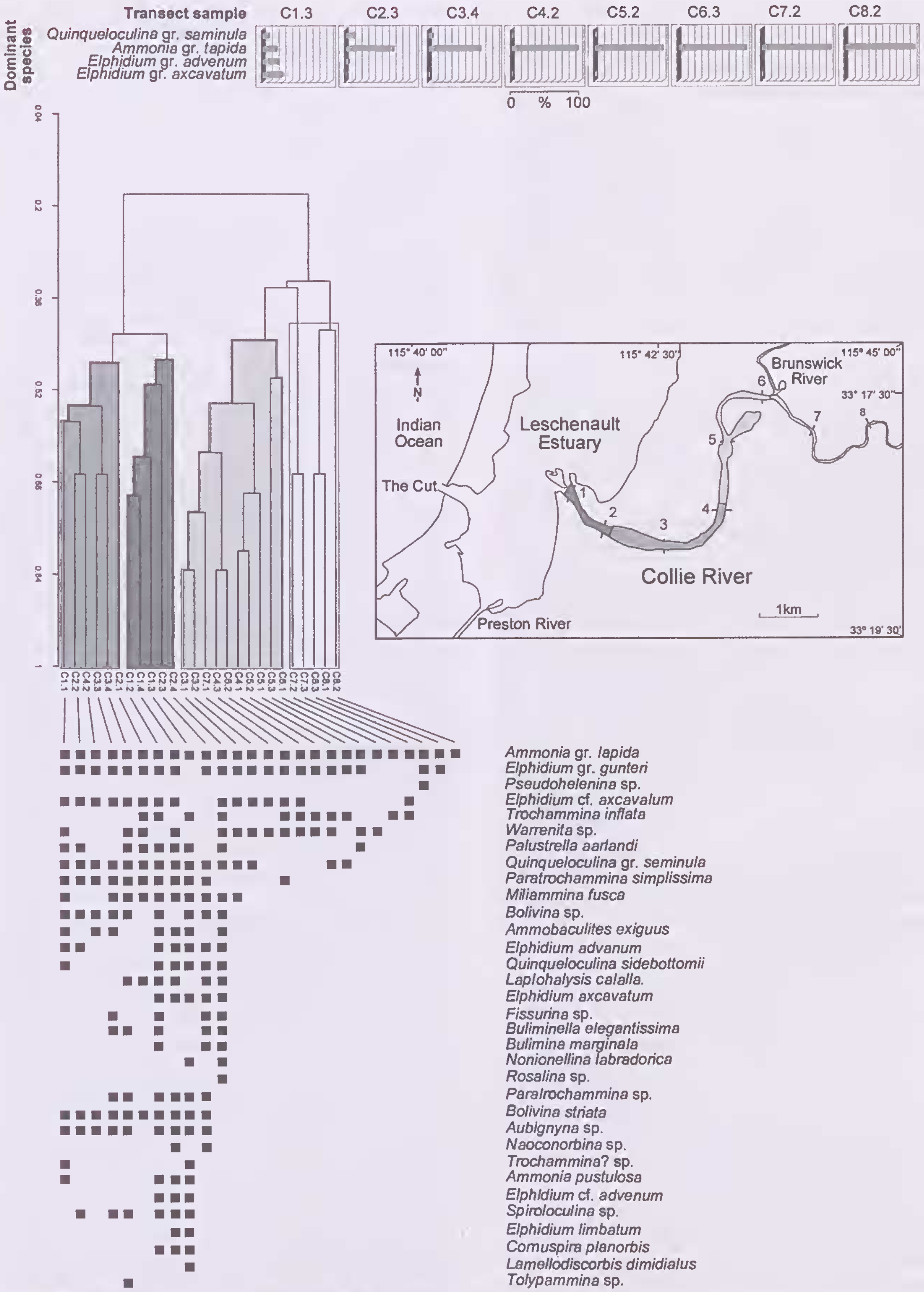

Figure 10 Distribution of foraminifera (total assemblage) from the Collie River during August 2005. Dominant species are those that have a frequency of ≥10% in one or more samples. The cluster analysis is based on the Jaccard Index and the UPGMA method in MVSP version 3.1.

and M8.2 were influenced by bottom-water anoxia during the April sampling period, whereas site M8.3 was well oxygenated which may explain its greater foraminiferal diversity compared to other samples in the upper tidal reaches of the river.

The most diverse foraminiferal microfauna found in any of the rivers was in the lower reaches of the Collie River, with 33 species identified, nine agglutinated, four porcelaneous and 20 hyaline (Figure 10). Four species groups have frequencies greater than 10% of the total foraminiferal assemblage in at least one of the studied sites in the river (Figure 10). Of these, *Ammonia* gr. *tepida* is the only species present in each transect; *Quinqueloculina* gr. *seminula* is present in transects 1–4; *Elphidium* gr. *advenum* is confined to transects 1–4; and *Elphidium* gr. *excavatum* has a broader range in transects 1–7.

Based on presence–absence foraminiferal distributions, four clusters of samples are distinguished in the Collie River (Figure 10), defined by decreasing diversity upstream. The most diverse cluster, with 31 species, includes samples from transects 1 and 2 at the mouth of the river. Species confined to the cluster include hyaline *Bulimina marginata*, *Cornuspira planorbis*, *Elphidium* cf. *advenum*, *Elphidium limbatum*, *Elphidium excavatum*, *Lamellodiscorbis dimidiatus*, *Neoconorbina* sp., *Nonionellina labradorica* and *Rosalina* sp. A second cluster which includes samples from transects 1–4 has 23 species including agglutinated *Tolypammina* sp. found only in this cluster at a single locality, and agglutinated *Ammobaculties exiguus*, *Leptohalysis catella*, *Paratrochammina* sp. and *Trochammina*? sp., porcelaneous *Quinqueloculina sidebottomii* and *Spiroloculina* sp., and hyaline *Ammonia pustulosa*, *Aubignyna* sp., *Buliminella elegantissima*, *Elphidium advenum*, *Fissurina* sp. and *Bolivina striata* shared with the first cluster described above. A third cluster includes samples from transects 3–7 and is characterised by much lower diversity, with eight species present, than the clusters downstream. The most persistent group in this cluster is hyaline *Ammonia* gr. *tepida* present in each sample. Hyaline *Elphidium* gr. *gunteri* and agglutinated *Warrenita* sp. are present in nine of the 10 samples. Porcelaneous *Quinqueloculina* gr. *seminula* has a sporadic occurrence in samples of the cluster, whereas it is present in each sample of the downstream clusters. Other species sporadically occurring here but more common downstream include agglutinated *Miliammina fusca*, *Palustrella earlandi* and *Paratrochammina simplissima*. Hyaline *Elphidium* cf. *excavatum* and agglutinated *Trochammina inflata* are more persistent and occur both in clusters downstream and upstream. The least diverse cluster includes samples from transects 6–8 in the upstream reaches of the tidal river. Here five species are present including *Ammonia* gr. *tepida* which is present in all samples. Hyaline *Pseudohelenina* sp. is found only in this cluster.

The influence of bathymetry on salt-wedge distribution, and variations in foraminiferal assemblage composition within a single transect are most evident in the Collie River compared to the other rivers. Upstream of transect 2 in the Collie River, the majority of species are confined to the deepest samples in transects C3 and C4. In transect 3, seven species are identified in samples C3.1 or C3.2, whereas 18 species identified in samples C3.3 or C3.4. Sample C4.2, the deepest site along transect 4, although located further upstream, has a similar diversity to samples C3.1 or C3.2.

DISCUSSION

Interpretation of our results is qualified by: (i) an assumption that the Rose-Bengal stained specimens represent living foraminifera; (ii) the very low abundance of stained foraminifera that precludes statistical analysis of their distribution patterns; and (iii) a lack of data on sediment mobility within the rivers. During the dry season, because of microtidal conditions and lack of freshwater outflow, there may be little sediment transport in the rivers. However in the wet season, the increased freshwater outflow may lead to down-river transport of sediment, including foraminiferal tests. The results we present should be considered preliminary until more detailed investigations can be made. However, our results suggest that similar trends in foraminiferal distribution patterns are present in each river and we make some tentative conclusions about these patterns.

Faunal diversity is most probably influenced by the amount of variation in salinity that occurs during the year and the residence times of normal-marine salinity (as against hyposaline and hypersaline conditions) during the dry season. The Collie River with the least variation in salinity (up to 32) has the most diverse assemblage at least in the lower reaches of the river where bottom waters maintain stable normal-marine conditions throughout the year. Some normal-marine species have apparently been able to migrate into the Collie River from the Leschenault Inlet without encountering any substantial low-salinity barrier throughout the year. The Serpentine River with the most variation in salinity (up to 51) has the least diverse assemblage. Species with low tolerance to variable salinity apparently have had difficulty migrating into this river (and the adjacent Murray River) because of the low salinity during winter in Peel Inlet and the absence of a salt wedge in the lower reaches of the rivers during this season.

The distribution of *Ammonia* gr. *tepida*, present among the total assemblage at each site in each river, suggests that it is the species most tolerant of salinity variation. During the wet season, live *A.* gr. *tepida* was found in very low salinities in the Serpentine River upstream to transect 5, in the Murray River upstream to transect 8, and in the Collie River upstream to the highest transect sampled during August. Similarly live *Elphidium* gr. *gunteri*, although more sporadic than *A.* gr. *tepida*, was found to have a broad distribution upstream during the wet season. In the Serpentine and Murray Rivers, other species were only found live during the dry season, and presumably are transported into the river with an advancing salt wedge. The sharp decrease in diversity in transects 3 and 4 of the Collie River compared to transects 1 and 2, suggests that the upper tidal reaches of this river experience similar conditions to the tidal reaches of the Serpentine and Murray Rivers, and this is evidenced by similarities in the faunal assemblages.

Based on the distributions of the live hyaline and porcelaneous foraminifera in all rivers (Figure 7), the order of tolerance to salinity changes seems to be: *Ammonia* gr. *tepida* with highest tolerance; *Elphidium* gr. *gunteri*, *E.* gr. *excavatum* and *E.* gr. *advenum* with slightly lower tolerance; *Quinqueloculina* gr. *seminula* with moderate tolerance; and *Cornuspira planorbis*, *Bolivina striata*, *Rosalina* sp. *Aubignyna* sp., *Bolivina* sp., *Buliminella elegantissima*, *Fissurina* sp., *Bulimina marginata*, *Quinqueloculina sidebottomii*, *Neoconorbina* sp. and *Ammonia pustulosa* with low tolerance. Among the organic-cemented agglutinated foraminifera, based on total assemblages, the distribution of *Ammobaculites exiguus* in the Serpentine River suggests that it has high tolerance to salinity changes. However, this species was rare in the nearby Murray River (found at one site in the lower reaches) and was absent from the Collie River. The substrate type and the organic content of the sediment do not seem to control the distribution of *Ammobaculites* here, and some unknown factor must be involved. *Trochammina inflata*, *Warrenita* sp. probably have moderate tolerance to salinity changes; whereas *Palustrella earlandi*, *Paratrochammina simplissima*, *Miliammina fusca*, *Leptohalysis catella*, *Paratrochammina* sp., *Trochammina*? sp. and *Tolypammina* sp. probably have lower tolerance. Calcite-cemented agglutinated foraminifera are absent from the rivers in contrast to their dominance in open-marine agglutinated assemblages along the southwest Australian coast (Haig 2002).

A detailed biogeographic analysis of the fauna is beyond the scope of this paper and awaits more comprehensive studies of other estuaries in the region. However, some preliminary biogeographic observations can be made. In southwest Australia, foraminiferal assemblages comparable to those found in the studied rivers were recorded by Quilty (1977) in the tidal reaches of the Blackwood–Scott river system leading into Hardy Inlet, and from the upper tidal reaches of the Swan River (Corr 1998). Studies of seasonal variation in the foraminiferal distributions have not been made in these rivers. Like the Collie River, the Blackwood–Scott river system has seasonal salinity variation of up to about 30 and the rivers show a similar rapid decrease in foraminiferal diversity upstream from the main inlet, from a moderately high number of species in the inlet (47 in Hardy Inlet) to assemblages with dominant *Ammonia* gr. *tepida* and very few other species in the upper tidal river system. In the upper tidal reaches of the Swan River, Corr (1998) also recorded *Ammonia* gr. *tepida* as the dominant species group, with *Elphidium* gr. *gunteri* and *Elphidium* gr. *excavatum* present, but in much lower proportions. Sediment in the Swan Estuary in the lower reaches of the river has a much more diverse foraminiferal assemblage (Quilty & Hosie 2006) than that found in any sample from the Serpentine, Murray and Collie Rivers but the total assemblage described there may include a large component derived from mid-Holocene highstand (normal-marine) deposits that outcrop around the estuary (Yassini & Kendrick 1988).

Yassini & Jones (1995) reviewed southeast Australian estuaries, coastal lagoons and tidal rivers. In contrast to the Mediterranean climate of southwest Australia, southeast Australia has a warm temperate climate with hot wet summers and cool to mild wet winters. The seasonal salinity variation in estuaries and tidal rivers is therefore not as large as recorded in the southwest tidal rivers and estuaries. Although assemblage distributions comparable to those found in the Serpentine, Murray and Collie Rivers are not obvious in the eastern Australian rivers there are some interesting similarities and differences in species distributions. For example, Yassini & Jones (1995) showed that *Ammonia* gr. *tepida* (recorded as *A. beccarii*) and *Ammobaculites exiguus* (as *Ammobaculites agglutinans*) have widespread distributions throughout estuarine environments. *Elphidium* gr. *gunteri* (as *Cribroelphidium vadescans*), is limited to coastal lagoon environments, and *Leptohalysis* sp., *Milliamina fusca* and *Trochammina inflata* also inhabit coastal lagoons. *Fissurina* sp. (=*F. lucida*), *Rosalina* sp., *Spiroloculina* spp. and *Bolivina* sp. prefer marine environments, and in brackish environments will only inhabit inlet channels. *Quinqueloculina* gr. *seminula* is the most widespread porcelaneous species in the brackish environments. These distribution patterns broadly mirror those found in southwest Australia, except that *Elphidium* gr. *gunteri* seems to have a more confined occurrence in the southeastern Australian estuaries and tidal rivers.

A comparison of foraminifera from brackish environments from southwest Western Australia and from other continents (Murray 1991, 2006) shows that a typical brackish-water assemblage is present in the Serpentine, Murray and Collie Rivers. There is, however, one unusual pattern in the foraminiferal distributions found in the studied rivers of southwest Australia. The upper regions of estuarine environments elsewhere are often dominated by organic-cemented agglutinated species (Murray 1991; Hayward *et al.* 1999; Scott *et al.* 2001; Debenay 2002). Although *Ammobaculites exiguus* is common in the Serpentine River, this pattern is not apparent in the Murray and Collie Rivers. Not only are there few organic-cemented agglutinated foraminifera throughout the latter rivers, but when the agglutinated species are present, their abundances are very low.

In a review of foraminifera from tropical paralic environments, Debenay (2000) showed approximate salinity ranges for *Ammonia* gr. *tepida* (5–80), *Elphidium* gr. *gunteri* (10–80), *Ammobaculites exiguus* (20–70), *Quinqueloculina* gr. *seminula* (10–60), that parallel, in order of salinity tolerance, the ranges found in southwest Australian rivers. The ranges recorded by Debenay (2002) are much broader than those found here, and the agglutinated species (*Ammotium salsum*, 1–105; *Haplophragmoides wilberti*, 2–100; *Arenoparrella Mexicana*, 1–100) with tolerances higher than the range of *Ammonia* gr. *tepida* have not been found in southwest Australia.

CONCLUSIONS

Three microtidal rivers studied in southwest Australia show large changes in salinity from the winter wet season to the summer dry season. The largest change, measured from August 2005 (during peak freshwater outflow in winter) to April 2006 (negligible freshwater outflow at end of dry season) was found to be 51 in the Serpentine River. The Murray River showed a maximum change of 38, whereas in the Collie River the maximum change was 32. The Collie River was the only river with a salt wedge of normal salinity at its mouth (in the deepest part of its central channel) during winter. Estuarine lagoon waters between the Collie River mouth and the open-sea channel into the Leschenault Inlet remain within or only slightly below normal-marine salinity levels throughout the year. In contrast the Serpentine and Murray Rivers have well-mixed waters of very low salinity at their mouths during winter and open into the Peel Inlet, a broad shallow estuarine lagoon with winter salinities lower than 20. The seasonal changes in salinity in the tidal rivers and the adjacent estuarine lagoons and the changes in salinity upstream from the mouth of the river have apparently influenced the foraminiferal distributions. Preliminary findings from the present study are:

(1) Thirty-five foraminiferal species are recorded from the rivers including 11 organic-cemented agglutinated types, four porcelaneous species, and 20 hyaline forms. The majority of species are known from estuaries elsewhere. Thirty-three of the species are recorded from the Collie River, 14 from the Murray River, and 10 species from the Serpentine River. The agglutinated *Ammobaculites exiguus*, the porcelaneous *Quinqueloculina* gr. *seminula* and the hyaline *Ammonia* gr. *tepida, Elphidium* gr. *gunteri, E.* gr. *advenum* and *E.* gr. *excavatum* dominate total (dead + live) assemblages in various parts of the rivers.

(2) Only the Serpentine River shows a typical estuarine distribution pattern with organic-cemented agglutinated species common in the middle to upper reaches of the river; the other rivers have sparse agglutinated assemblages.

(3) Using total assemblages and cluster analysis, equivalent differentiation of faunas is recognised in each river with a consistent change in diversity upstream from the river mouth. The diversity of live hyaline and porcelaneous foraminifera (recognised from Rose-Bengal stained specimens) shows a similar decrease to that of the total assemblage.

(4) On the basis of the distribution of live foraminifera, *Ammonia* gr. *tepida* occupies the full salinity range (maximum of 51) recorded in the rivers. *Elphidium* gr. *gunteri, E.* gr. *excavatum* and *E.* gr. *advenum* have slightly less salinity tolerance and are only found here at salinities below 44. The dominant porcelaneous species *Quinqueloculina* gr. *seminula,* which in these rivers has a very thin test and small size, has moderate salinity tolerance (24-45).

These findings suggest that few species (e.g. *Ammonia* gr. *tepida, Elphidium* gr. *gunteri, E.* gr. *excavatum, E.* gr. *advenum*) overcome low salinity barriers to habitation in the rivers during winter. These species live permanently in the tidal reaches of the rivers although they probably reproduce only under favorable conditions during summer. Transport or migration within an advancing salt wedge, may explain the distributions of most of the other species found in the rivers with the most diverse assemblages present where a normal-marine salt wedge is maintained in the lower reaches of the river throughout the year (as in the Collie River).

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APPENDIX 1 LIST OF SPECIES

Species are arranged in alphabetical order. Previous illustrated records from rivers and coastal lagoons in southwest Australia are included below the name used in this study. Because of problems with taxonomy, as revealed for example in the molecular and morphological studies of Hayward *et al.* (2004) for species of *Ammonia*, broad groups are identified for some taxa. Illustrations on Figure 5 include those species that are dominant in the studied rivers, and those on Figure 6 are the less common species that have not been illustrated previously from southwest Australian rivers. Species identifications have been checked against original descriptions and illustrations available in the *Catalogue of Foraminifera* (www.micropress.org).

Ammonia* gr. *tepida (Cushman)
Figure 5 (1–6)

Streblus beccarii (Linné): McKenzie 1962, p. 125, pl. 3, figs. 18, 19: Oyster Harbour.
Ammonia beccarii (Linné): Quilty 1977, p. 90, figs. 45–47: Hardy Inlet.
Ammonia tepida (Cushman): Quilty 1977 p. 90, figs. 48, 49: Hardy Inlet.
Ammonia tepida (Cushman): Revets 2000, p. 371, pl. 3, figs. 16, 17: Leschenault Inlet.
Ammonia aoteana (Finlay): Quilty & Hosie 2006, pl. 1, figs. 21, 22: Swan Estuary.
Ammonia tepida (Cushman): Quilty & Hosie 2006, p. 314, pl. 1, figs. 25, 26: Swan Estuary.

Ammonia* gr. *pustulosa (Albani & Barbero)

Ammonia cf. *pustulosa* (Albani & Barbero): Quilty & Hosie 2006, p. 314, pl. 1, figs. 23, 24: Swan Estuary.

Ammobaculites exiguus Cushman and Bronnimann
Figure 5 (13, 20)

Ammobaculites agglutinans (d'Orbigny): McKenzie 1962, p. 119, pl. 1, fig. 4: Oyster Harbour.
Ammobaculites agglutinans (d'Orbigny): Quilty 1977, p. 89, fig. 10: Hardy Inlet.
Ammobaculites agglutinans (d'Orbigny): Quilty & Hosie 2006, pl. 1, fig. 1: Swan Estuary.

Aubignyna sp.
Figure 6 (1–3)

Bolivina striatula Cushman

Bolivina striatula Cushman: Revets 2000, p. 371, pl. 2, figs. 53, 54: Leschenault Inlet.

Bolivina sp.

Bolivina brittanica Macfadyen: Revets 2000, p. 371, pl, 2, figs. 45, 46: Leschenault Inlet.

Bulimina marginata d'Orbigny
Figure 6 (4)

Buliminella elegantissima d'Orbigny
Figure 6 (5)

Cornuspira planorbis Schultze

Cornuspira planorbis Schultze: Revets 2000, p. 370, pl. 1, figs. 36, 37: Leschenault Inlet.

Elphidium advenum (Cushman)
Figure 5 (9, 10)

Elphidium cf. *advenum* (Cushman) (Figure 5 nos. 11, 12)
Elphidium sp 1: Revets 2000 p. 371, pl 4, figs. 11, 12: Leschenault Inlet.

Elphidium excavatum (Terquem)
Figure 5 (14, 15)

Elphidium* cf. *excavatum (Terquem)
Figure 5 (16, 17)

Elphidium excavatum (Terquem): Quilty & Hosie 2006, p. 314, pl. 1, fig. 28: Swan Estuary.

Elphidium* gr. *gunteri Cole
Figure 5 (7, 8)

Elphidium reticulosum Cushman: Revets 2000, p. 371, pl. 4, figs. 9, 10: Leschenault Inlet.
Elphidium gunteri Cole: Quilty & Hosie 2006, p. 314, pl. 1, fig. 29: Swan Estuary.

Elphidium limbatum (Chapman)

Elphidium limbatum (Chapman): Revets 2000, p. 371, pl. 4, figs. 7, 8: Leschenault Inlet.

Elphidium sp.

This species is represented by very few specimens and is not illustrated.

Fissurina sp.

Fissurina sp.: Revets 2000, p. 371, pl. 2, figs. 40, 41: Leschenault Inlet.

Haplophragmoides sp.

This species is represented by very few specimens and is not illustrated.

Leptohalysis catella (Höglund)

Leptohalysis catella (Höglund): Revets 2000, p. 370, pl. 1, figs. 9, 10: Leschenault Inlet.

Lamellodiscorbis dimidiatus (Jones & Parker)

Discorbis dimidiatus (Jones & Parker): McKenzie 1962, p. 125, pl. 3, figs. 7, 8: Oyster Harbour.
Discorbis dimidiatus (Jones & Parker): Quilty 1977, p. 89, figs. 31, 32: Hardy Inlet.

Miliammina fusca (Brady)

Miliammina fusca (Brady): McKenzie 1962, p. 119, pl. 1, fig. 1: Oyster Harbour.
Miliammina fusca (Brady): Quilty 1977, p. 89, fig. 9: Hardy Inlet.
Miliammina fusca (Brady): Revets 2000, pl. 1, figs 11, 12: Leschenault Inlet.

Neoconorbina sp.
Figure 6 (6, 7)

Nonionellina labradorica (Dawson)

Nonionellina labradorica (Dawson): Revets 2000, p. 371, pl. 4, figs. 33, 34: Leschenault Inlet.

Paratrochammina simplissima (Cushman & McCulloch)

Paratrochammina simplissima (Cushman & McCulloch): Revets 2000, p. 370, pl. 1, figs. 17, 18: Leschenault Inlet.

Paratrochammina sp.
Figure 6 (8–10)

Palustrella earlandi (Parker)

Textularia earlandi Parker: Revets 2000, p. 370, pl. 1 figs. 25, 26: Leschenault Inlet.

Pseudohelenina sp.

This species is represented by very few specimens and is not illustrated.

***Quinqueloculina* gr. *seminula* (Linnaeus)**
Figure 5 (18, 19)

Quinqueloculina seminula (Linnaeus): Revets 2000, p. 370, pl. 2, figs. 3, 4: Leschenault Inlet.

Quinqueloculina seminula (Linné): Quilty 1977, figs 15, 16: Hardy Inlet.

***Quinqueloculina littoralis* (Collins)**

Quinqueloculina striata d'Orbigny: Quilty 1977, p. 89, fig. 20: Hardy Inlet.

Triloculina littoralis Collins: Revets 2000, p. 371, pl. 2, figs. 25, 26: Leschenault Inlet.

***Rosalina* sp.**
Figure 6 (11–13)

***Spiroloculina* sp.**
Figure 6 (14, 15)

***Tolypammina* sp.**

This species is represented by very few specimens and is not illustrated.

***Trochammina inflata* (Montagu)**

Trochammina inflata (Montagu): McKenzie 1962, p. 119, pl. 1, figs. 7, 8: Oyster Harbour.

***Trochammina*? sp.**
Figure 6 (16–18)

***Warrenita* sp.**

Protoshista findens (Parker): Quilty 1977, p. 89, fig. 8: Hardy Inlet.

SUPPLEMENTARY PAPERS

Table 1 Location of samples (latitude and longitude) and water quality measurements: depth (m), temperature (°C), pH, salinity, dissolved oxygen (% saturation).

Table 2 Summary of sediment characteristics.

Table 3 Distribution of living foraminifera, Serpentine River.

Table 4 Distribution of living foraminifera, Murray River.

Table 5 Distribution of living foraminifera, Collie River.